Received 22 June 2023, accepted 10 July 2023, date of publication 17 July 2023, date of current version 21 July 2023.
Digital Object Identifier 10.1109/ACCESS.2023.3296226

RESEARCH ARTICLE

Image Enhancement Technique Using Manchester Coding and RF Tripler for 1-bit Bandpass Delta Sigma Direct Digital RF Transmitter

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This work was supported by the Cooperative Research Project Program of the Research Institute of Electrical Communication, Tohoku University.

ABSTRACT 1-bit band-pass delta-sigma modulator (BP-DSM) can generate RF signal directly from 1-bit data stream in high dynamic range by oversampling technology without local oscillator (LO) and mixer, so the miniaturization of transmitter can be realized. Meanwhile, to generate RF signal in high frequency band, direct digital RF transmitter using image components of 1-bit signal folded in high Nyquist zone has been studied. In a previous study, an image enhancement 1-bit digital-to-analog converter (DAC) based on a high-speed inverter has been proposed to regenerate or enhance the high order image components of 1-bit BP-DS modulated signal which attenuate severely because of the transmission loss. However, a high-speed inverter is very complex and difficult to implement. Consequently, only low order (1^{st} or 2^{nd}) image components can be used in direct digital RF transmitter. In this paper, firstly, we propose an image enhancement technique using Manchester coding and RF tripler instead of 1-bit DAC based on inverter and illustrate its principle. By the theoretical calculation, simulation and measurement, the feasibility has been proven. In the measurement, 1-bit data in Manchester code is applied whose amplitude and datarate are set to $1V_{pp}$ and 2 Gbps, respectively. It is confirmed that, because of the nonlinearity of RF tripler, both in the continuous wave (CW) and 5Msps-QPSK condition, the high order image components of 1-bit BP-DS modulated signal in Manchester code can be regenerated with a good characteristics of noise shaping. In CW condition, the measured output power of regenerated high order image components at 6^{th} (5.5 GHz) and 7^{th} (6.5 GHz) Nyquist zone are −22.4 dBm and −24.9 dBm, respectively. After the peak-to-peak amplitude of measured signal is normalized in MATLAB, the output power of regenerated high order image components are −9.1 dBm and −11.6 dBm, respectively, which is very close to ideal 1-bit data in Manchester code. The measurement results have a good agreement with the theoretical calculation and simulation. In the QPSK condition, the measured output power of regenerated high order image components at 6^{th} (5.5 GHz) and 7^{th} (6.5 GHz) Nyquist zone are −25.3 dBm and −27.8 dBm, respectively. After the peak-to-peak amplitude of measured signal is normalized in MATLAB, the output power of regenerated high order image components are −11.9 dBm and −14.5 dBm, respectively. It is proven that the illustrated principle of image enhancement is reasonable and proposed image enhancement technique using Manchester coding and RF tripler is effective. Compared with direct digital RF transmitter only using low order (1^{st} or 2^{nd}) image components in previous work, the proposed image enhancement technique can regenerate or enhance the high order ((5^{th} or 6^{th})) image components and contribute to direct digital RF transmitter operating in higher frequency with lower datarate.

INDEX TERMS Image enhancement, tripler, band-pass delta-sigma modulator, 1-bit modulator, digital RF, Manchester coding, microwave, transmitter, 5G.

The associate editor coordinating the review of this manuscript and approving it for publication was Deepak Mishra.

I. INTRODUCTION

In recent years, digital beamforming (DBF) transmitter which has higher spectrum efficiency and larger coverage than conventional transmitter, has been studied for the application of 5G and next generation mobile communication systems [1], [2], [3], [4]. DBF transmitter consists of multiple antenna elements. Consequently, every antenna element needs a transmitter. In addition, the distance of each element is only about 0.5λ, (λ: wavelength), which means that the element transmitters are very close to each other. As a result, the miniaturization of the transmitter is necessary.

To realize the miniaturization, the digital RF technology [5], [6], [7] proposed to generate RF signal directly from digital circuit without analog circuit is considered suitable for DBF transmitter. In previous research, digital RF transmitter using 1-bit band-pass delta-sigma modulator (BP-DSM) has been studied for a long time [8], [9], [10], [11], [12]. Since it can generate RF signal in high dynamic range from the 1-bit BP-DS modulated signal directly without up-conversion, the local oscillator (LO) and mixer can be removed to realize the miniaturization as shown in Fig. 1.

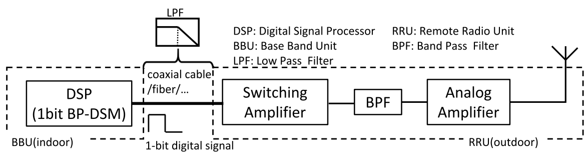


FIGURE 1. 1-bit digital transmitter.

Furthermore, to generate RF signal in high frequency band beyond Nyquist limit, the digital RF transmitter using 1st image component of 1-bit BP-DS modulated signal has been proposed [13], [14]. However, only using 1st image component whose frequency is below the datarate is not enough for signal generation in high frequency band. So we proposed the direct digital RF transmitter using its high order image components, to generate RF signal in higher frequency band [15], [16], [17], [27].

Meanwhile, to enhance the image component at specific Nyquist Zone before the transmission, different coding schemes, such as NRZ, RZ and Manchester coding [19], have been discussed [14], [16], [17], [18]. Manchester coding has been proven to be an effective coding scheme to enhance the image components of the 1-bit BP-DS modulated signal at specific (4n-1)th and (4n-2)th Nyquist Zone by theoretical calculation, simulation and measurement [20]. As shown in Fig. 2, Manchester coding can be realized simply by XOR gate without any other components. Compared with the similar coding scheme, polar RZ coding which has three states, the implementation of Manchester coding is much simpler. Moreover, in polar RZ coding, the DC component will drift as the probability distribution of data '1' changes and the clock leakage will occur. However, despite how the probability distribution of data '1' changes, the DC component of 1-bit BP-DS modulated signal in Manchester code remains constant and there will be no clock leakage. Consequently,

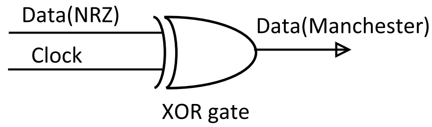


FIGURE 2. Manchester coding.

Manchester coding has advantages on simple implementation and DC balance.

On the other hand, 1-bit BP-DSM is very suitable for optical fiber transmission in the DBF system because of its flexibility and low-cost [3], [4], [21], [22], [23]. Digital RF transmitter using image component of 1-bit BP-DSM has also been demonstrated in optical fiber transmission [24], [25], [26]. However, because of the transmission loss, the high order image components of 1-bit BP-DS modulated signal attenuate severely and only the fundamental or the 1st image component of 1-bit BP-DS modulated signal is utilized after optical fiber transmission [24], [25], [26].

To regenerate the high order image components of 1-bit BP-DS modulated signal, an image enhancement type 1-bit digital-to-analog converter (DAC) based on inverter has been proposed [28]. In [28], the high order image components are regenerated by the clipping/limiting operation of inverter. Therefore, a high-speed inverter is necessary which is very difficult to implement. Moreover, the principle of image enhancement (how the image components are regenerated or enhanced) has not been illustrated.

In this paper, firstly, the principle of image enhancement is illustrated. Then, instead of image enhancement type 1-bit DAC [28] based on a high-speed inverter, we propose the image enhancement technique using Manchester coding and RF tripler to enhance or regenerate the high order image components of 1-bit BP-DS modulated signal. In Sect. II, the principle of image enhancement is illustrated by the theoretical calculation with the reasonability of using RF tripler (odd-order RF multiplier). In Sect. III, the simulation using 1-bit data in Manchester code is conducted by advanced design system (ADS) to confirm the theoretical calculation. The simulation result of the proposed image enhancement is presented and compared with the ideal 1-bit signal in NRZ and Manchester code. In Sect. IV, to verify the calculation and simulation, the measurement results are presented. Finally, Sect. V is conclusion.

II. PRINCIPLE OF IMAGE ENHANCEMENT TECHNIQUE USING MANCHESTER CODING AND RF TRIPLER

In [28], it has been proven that 1-bit DAC based on inverter can enhance or regenerate the high order image components of lowpass filtered 1-bit BP-DS modulated signal by sharpening the rising/falling time of signal.

However, it is just phenomenon-based observation and can not explain the principle. To illustrate the principle of image enhancement, the behaviour of 1-bit DAC based on inverter should be modelized mathematically and specifically. Since it is a nonlinear device, its output-input function in time domain can be simplified by (1).

$$y(t) = \sum_{i=0}^{+\infty} a_i * x^i(t) \tag{1}$$

Obviously, the image components can only be regenerated or enhanced by its nonlinear response. So the theoretical calculation of its nonlinear response when n is supposed to be 2 (doubler) and 3 (tripler) will be conducted in this section to explain the principle of image enhancement. Then, the calculation results under the condition of Manchester coding are presented.

A. COMPARISON BETWEEN USING RF DOUBLER AND TRIPLER IN THE ENHANCEMENT TECHNIQUE BY THEORETICAL CALCULATION

As RF multiplier, a nonlinear device, the ideal output-input function in time domain can be simplified by (2) [29].

$$y(t) = a * x^n(t). \tag{2}$$

n is order of RF multiplier, supposed to be 2 and 3, in the calculation of RF douber and tripler, respectively. Consequently, the input signal can only be consisted of the fundamental and low order image components since the high order image components of 1-bit BP-DS modulated signal, whose frequency is higher than bitrate, attenuate severely because of the transmission loss.

Moreover, since the Manchester coding was proposed to enhance the image components at specific $(4n\text{-}1)^{th}$ and $(4n\text{-}2)^{th}$ Nyquist Zone [20], only the 1st and 2nd image components of 1-bit BP-DS modulated signal are regarded as input signal. As a result, to simplify the calculation, it is supposed that a is normalized and input signal $x(t)=A\cos(2\pi f_{RF}t)+B\cos[2\pi(2f_c - f_{RF})t]$ in CW condition while f_{RF} is the frequency of RF signal and f_c is datarate which is half of the bitrate. After the calculation, the output signals y(t) of RF doubler and tripler are shown in (3) and (4), respectively.

1) IN THE CASE OF RF DOUBLER

$$\begin{aligned} y_{doubler}(t) &= \{Acos(2\pi f_{RF}t) + Bcos[2\pi(2f_c - f_{RF})t]\}^2 \\ &= 0.5A^2cos(2\pi * 2f_{RF}t) + 0.5B^2cos[2\pi(4f_c - 2f_{RF})t] \\ &\quad + ABcos(2\pi * 2f_ct) + ABcos[2\pi(2f_c - 2f_{RF})t] \\ &\quad + 0.5(A^2 + B^2) \end{aligned} \tag{3}$$

Obviously, from (3), there is no fundamental or image components in the output signal of RF doubler. So, theoretically, the RF doubler or second order nonlinear response of 1-bit DAC can not be used to enhance or regenerate the high order image component.

2) IN THE CASE OF RF TRIPLER

$$\begin{aligned} y_{tripler}(t) &= \{Acos(2\pi f_{RF}t) + Bcos[2\pi(2f_c - f_{RF})t]\}^3 \\ &= \underline{(0.75A^3 + 1.5AB^2)cos(2\pi f_{RF}t)} \\ &\quad \underline{+ (0.75B^3 + 1.5A^2B)cos[2\pi(2f_c - f_{RF})t]} \\ &\quad \underline{+ 0.75A^2Bcos[2\pi(2f_c + f_{RF})t]} \\ &\quad \underline{+ 0.75AB^2cos[2\pi(4f_c - f_{RF})t]} \\ &\quad + 0.25A^3cos(2\pi * 3f_{RF}t) \\ &\quad + 0.75A^2Bcos[2\pi(2f_c - 3f_{RF})t] \\ &\quad + 0.75AB^2cos[2\pi(4f_c - 3f_{RF})t] \\ &\quad + 0.25B^3cos[2\pi(6f_c - 3f_{RF})t] \end{aligned} \tag{4}$$

However, from (4), in the output signal of tripler, there are fundamental and image components (f_{RF}) which are marked by solid line and third harmonic components ($3f_{RF}$)which are marked by dash line. Obviously, the third harmonic components are undesired interference signal. For the modulation signal, the bandwidth of third harmonic components is three times wider than the fundamental and image components. Nevertheless, it still can be confirmed that the high order image components whose frequency is beyond the bitrate are regenerated by RF tripler or third order nonlinear response of 1-bit DAC.

The theoretical calculation can be extended to higher order RF multiplier, such as RF quadrupler, quintupler and so on. As a result, the high order image component of lowpass filtered 1-bit BP-DS modulated signal can only be regenerated by odd-order RF multiplier instead of even-order RF multiplier.

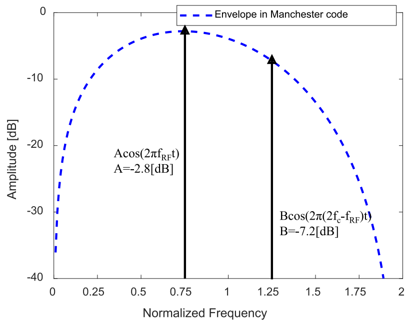
B. CALCULATION RESULT USING RF TRIPLER UNDER THE CONDITION OF MANCHESTER CODE

Previously, the principle of image enhancement was illustrated qualitatively. However, to verify it by the simulation and measurement, quantitative calculation is necessary. The calculation result using RF tripler under the condition of Manchester code is shown as follows.

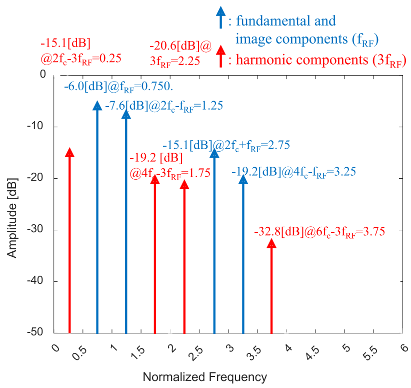
To eliminate the unused image component at adjacent Nyquist zone easily and to stabilize the BP-DSM, usually, the center frequency of BP-DSM, which is the frequency of RF signal, is set around quarter of datarate, $0.25f_c$. Since the 1st image component of 1-bit BP-DS modulated signal in Manchester code is regarded as RF signal, the frequency of RF signal is $0.75f_c$.

The calculation result of input and output spectrums of RF tripler in Manchester code is shown in Fig.3(a), (b), respectively. The frequency is normalized by datarate or half of the bitrate. The amplitude of 1-bit signal is also normalized.

From the calculation results, in Manchester code condition, the regenerated image components at the normalized frequency of 2.75 and 3.25 with the output power of −15.1 dB and −19.2 dB can be confirmed in normalized amplitude.



(a) Input spectrum of RF tripler



(b) Output spectrum of RF tripler

FIGURE 3. Calculation result of input and output spectrums of RF tripler in Manchester code.

Since the datarate is half of bitrate, all harmonic components are separated from the image components, which may improve the signal-to-noise ratio (SNR). In fact, as shown in Fig.3(a), (b), it is very clear that the high order image components can be regenerated by part of the third order intermodulation of input signal.

Meanwhile, it must be noticed that the calculation is conducted using an ideal model, $y(t)=x^3(t)$. Obviously, it has not taken the practical implementation into the consideration which leads the limitation in practical. As shown in (4), the output power of RF tripler will degrade/increase by 3 dB as the input power degrades/increases by 1 dB. But, actually, in the practical implementation, as nonlinear RF device, the RF tripler is usually implemented by transistors or diodes which are biased around the saturation or pinch-off region. It limits the conversion gain. As a result, the output power is limited in practical implementation because of the device characteristics.

However, even if there are some limitations of the ideal calculation, the result of theoretical calculation can explain the principle of the proposed image enhancement technique using RF tripler qualitatively and has a good agreement to simulation and measurement in CW condition which will be shown in the following sections.

As a conclusion of this section, after the principle of image enhancement is illustrated qualitatively, it is proven that the proposed image enhancement technique using Manchester coding and RF tripler is reasonable and effective by theoretical quantitative calculation.

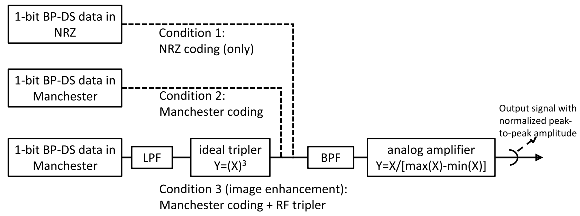


FIGURE 4. Simulation setup.

III. SIMULATION RESULT

To verify the principle and calculation result of image enhancement technique using Manchester coding and RF tripler in previous section, the simulation is conducted by ADS.

A. SIMULATION SETUP

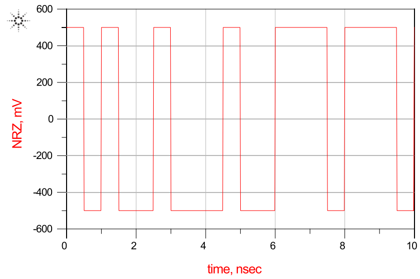
First, the RF signal whose frequency is 0.501 GHz is modulated to 1-bit digital signal in NRZ and Manchester code whose amplitude and datarate are $1V_{pp}$ and 2 Gbps, respectively. The ideal Butterworth lowpass filter whose cutoff frequency is 3.5 GHz is applied to imitate the transmission loss. The lowpass filtered 1-bit BP-DS modulated signal in Manchester code is regarded as input signal of ideal RF tripler. To verify the proposed image enhancement technique, the ideal 1-bit BP-DS modulated signal in both NRZ and Manchester code without lowpass filter is also applied in the simulation as shown in Fig.4.

Then, the bandpass filter whose passband is from 4 (5^{th} Nyquist zone) to 8 (8^{th} Nyquist zone) GHz is used to extract regenerated image and harmonic components. As shown in Fig. 1, the last component before antenna is analog amplifier. Because the maximum swing of analog amplifier is limited by supply voltage, the output power should be evaluated with the normalized peak-to-peak amplitude. So, the gain of analog amplifier is supposed to be 1/[max(input)-min(input)]. In this section, all spectrums are shown in resolution bandwidth (RBW) of 100 KHz.

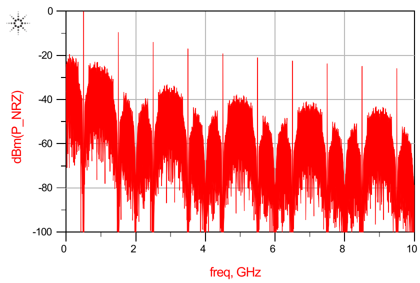
B. IN CONDITION OF IDEAL 1-BIT BP-DS MODULATED SIGNAL IN NRZ CODE

The waveform and spectrum of ideal 1-bit BP-DS modulated signal in NRZ code is shown in Fig.5(a), (b), respectively. In the simulation, only quantization noise is considered, so the same characteristics of noise shaping for all fundamental and image components can be confirmed in every Nyquist zone.

The spectrum without/with normalized peak-to-peak amplitude of bandpass filtered ideal 1-bit BP-DS modulated signal in NRZ code is shown in Fig.6(a), (b), respectively. After the peak-to-peak amplitude of bandpass filtered ideal 1-bit BP-DS modulated signal in NRZ code is normalized, the

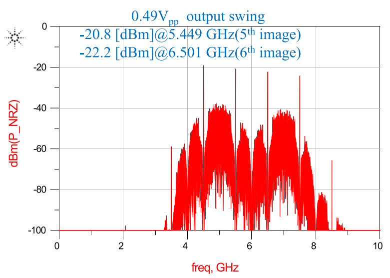


(a) Waveform

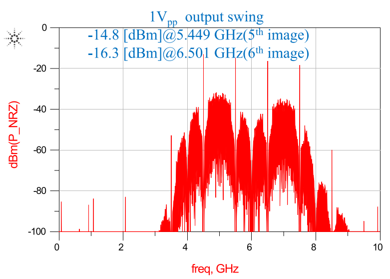


(b) Spectrum

FIGURE 5. Simulation result of ideal 1-bit BP-DS modulated signal in NRZ code.



(a) Spectrum without normalized peak-to-peak amplitude



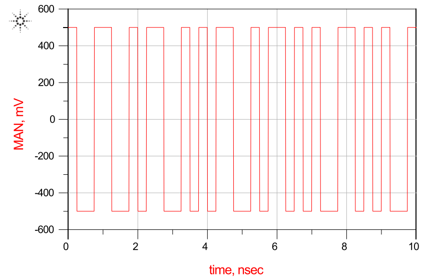
(b) Spectrum with normalized peak-to-peak amplitude

FIGURE 6. Simulation result of bandpass filtered ideal 1-bit BP-DS modulated signal in NRZ code.

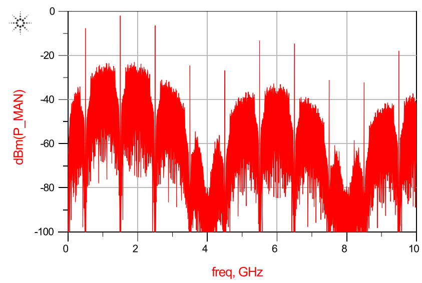
output power of 5^{th} and 6^{th} image component are -14.8 dBm and -16.3 dBm, respectively.

C. IN CONDITION OF IDEAL 1-BIT BP-DS MODULATED SIGNAL IN MANCHESTER CODE

The waveform and spectrum of ideal 1-bit BP-DS modulated signal in Manchester code is shown in Fig.7(a), (b), respectively. Same in NRZ code, the same characteristics of noise shaping for all fundamental and image components can be confirmed in every Nyquist zone. The spectrum without/with normalized peak-to-peak amplitude of bandpass filtered ideal 1-bit BP-DS modulated signal in Manchester code is shown in Fig.8(a), (b), respectively. After the peak-to-peak amplitude of bandpass filtered ideal 1-bit BP-DS modulated signal in Manchester code is normalized, the output power of 5^{th} and 6^{th} image component are -7.8 dBm and -9.3 dBm, respectively.



(a) Waveform



(b) Spectrum

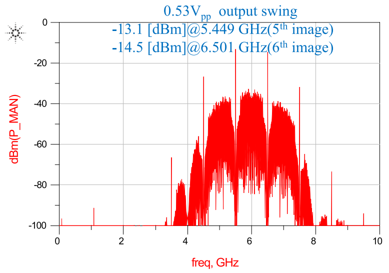
FIGURE 7. Simulation result of ideal 1-bit BP-DS modulated signal in Manchester code.

D. IN CONDITION OF IMAGE ENHANCEMENT USING MANCHESTER CODING AND RF TRIPLER

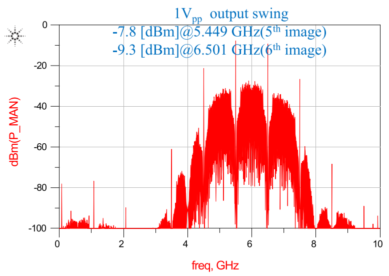
As mentioned, the ideal Butterworth lowpass filter whose cutoff frequency is 3.5 GHz is applied to imitate the transmission loss. The lowpass-filtered 1-bit signal in Manchester code is regarded as input signal of RF tripler, whose spectrum is shown in Fig.9(a). Because of the limitation of bandwidth, the high order image components of 1-bit BP-DS modulated signal are totally eliminated.

The spectrum of output of ideal RF tripler is shown in Fig.9(b). It can be confirmed that the high order image components at 5.5 GHz and 6.5 GHz are regenerated with a good noise shaping characteristics from overall spectrum, Fig.9(b). The enlarged spectrums of regenerated image components at 5.5 GHz and 6.5 GHz are presented in Fig.10(a), (b), respectively. The output power of regenerated image components at 5.5 GHz and 6.5 GHz are -23.2 dBm and -25.9 dBm, respectively.

In the theoretical calculation, since only 1^{st} and 2^{nd} image components of 1-bit BP-DS modulated signal in Manchester is regarded as input signal, the harmonic components,

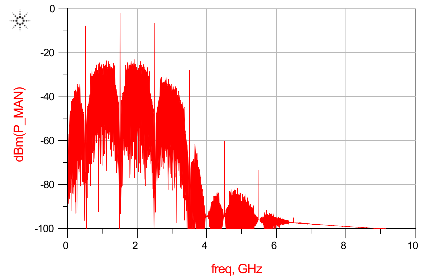


(a) Spectrum without normalized peak-to-peak amplitude

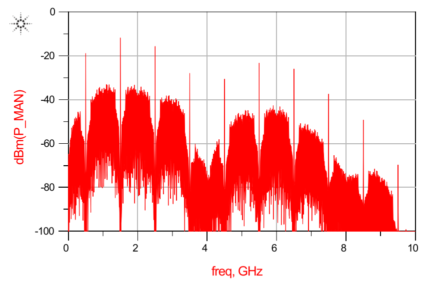


(b) Spectrum with normalized peak-to-peak amplitude

FIGURE 8. **Simulation result of bandpass filtered ideal 1-bit BP-DS modulated signal in Manchester code.**



(a) Spectrum of input signal of RF tripler



(b) Spectrum of output signal of RF tripler

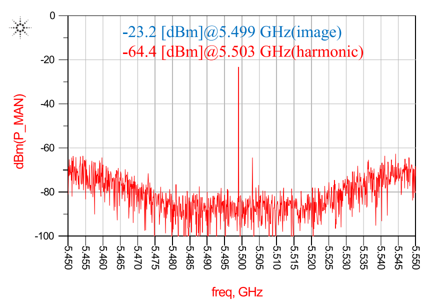
FIGURE 9. **Simulation result of image enhancement technique using RF tripler in Manchester code condition for 1-bit BP-DS modulated signal.**

as unused signal, are separated. But, in the simulation, the fundamental component is also part of input signal of RF tripler, so there are still some harmonic components close to image components that can be confirmed.

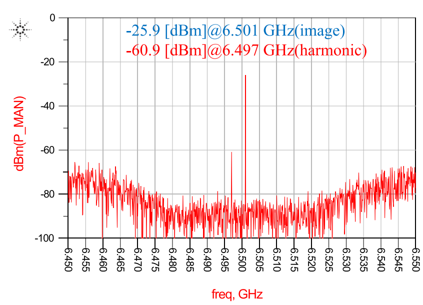
As shown in Fig.10, it's important that the power of harmonic components is about 35 dB lower than that of regenerated image components, which can prove our assumption and calculation reasonable in certain degree. It is predictable that in the condition of modulation wave, the adjacent channel leakage ratio (ACLR) can be beyond 40 dB theoretically. The simulated output power of regenerated image components is about 7 dB lower than the calculated one. Maybe it is because the noise components have not been considered in calculation. In the future work, noise components shall be modelized as well.

The spectrum without/with normalized peak-to-peak amplitude of bandpass filtered output signal of RF tripler is shown in Fig.11(a), (b), respectively. After the peak-to-peak amplitude of bandpass filtered output signal of RF tripler is normalized, the output power of 5^{th} and 6^{th} image component are -8 dBm and -10.8 dBm, respectively.

As a conclusion of this section, compared with ideal 1-bit BP-DS modulated signal in NRZ code, the proposed image enhancement technique using Manchester coding and RF tripler can regenerate the high order image components from the lowpass filtered 1-bit BP-DS modulated signal. The output power is very close to the simulation result in condition of ideal 1-bit BP-DS modulated signal in Manchester code with normalized peak-to-peak amplitude.



(a) Enlarged spectrum at 5.5 GHz



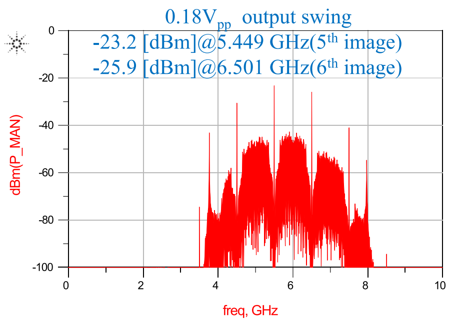
(b) Enlarged spectrum at 6.5 GHz

FIGURE 10. **Enlarged spectrums of output signal of RF tripler in Manchester code condition in simulation.**

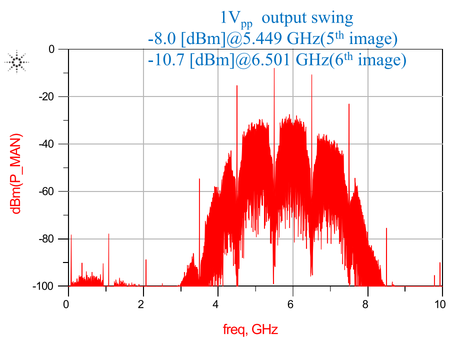
IV. MEASUREMENT RESULT

A. MEASUREMENT SETUP

For the further verification of the proposed image enhancement technique using Manchester coding and RF tripler, the measurements are conducted. The initial CW (f=0.501 GHz)and 5Msps-QPSK (f_c=0.5 GHz) RF signal are modulated by 1-bit BP-DSM to 1-bit data and then encoded in



(a) Spectrum without normalized peak-to-peak amplitude



(b) Spectrum with normalized peak-to-peak amplitude

FIGURE 11. **Simulation result of bandpass filtered output signal of RF tripler signal in Manchester code.**

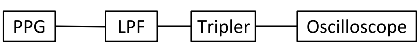


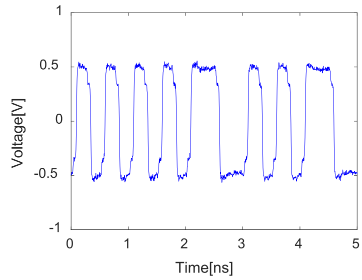
FIGURE 12. **Measurement setup.**

Manchester code in MATLAB. As measurement setup shown in Fig. 12, we used a pulse pattern generator(PPG, Anritsu M18020A) to generate $1V_{pp}$/2 Gbps 1-bit BP-DS modulated signal in Manchester code. To imitate the transmission loss and eliminate high order image components, the lowpass filter (LPF, Mini-circuits VLFG-3500+) whose cutoff frequency is 3.5 GHz is applied, same as in the simulation. Then, the lowpass filetered 1-bit signal is the input signal of RF tripler (Minicircuits ZX90-3-692-S+) whose input frequency is from 1.7 GHz to 2.3 GHz. At last, the waveform of output signal of RF tripler is observed by oscilloscope (Keysight-DSO-X 96204Q). The spectrums without/with normalized peak-to-peak amplitude are calculated by fast fourier transform (FFT) to confirm the frequency characteristics in MATLAB.

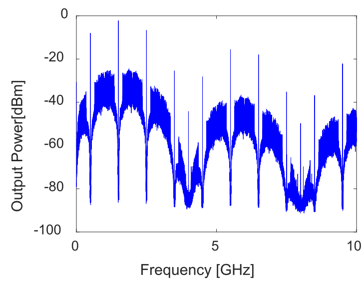
B. MEASUREMENT RESULT IN CW CONDITION

In CW condition, the measured waveform and spectrum of output signal of PPG, the 1-bit signal in Manchester code, is shown in Fig. 13(a), (b), respectively. The measured spectrum of input and output signal of RF tripler is shown in Fig. 14(a), (b) respectively.

From the measurement result, it is confirmed that the high order image components of 1-bit BP-DS modulated signal in

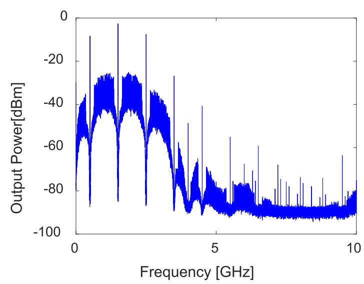


(a) Waveform

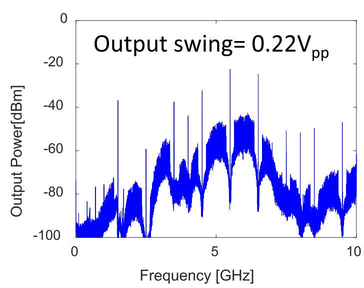


(b) Spectrum

FIGURE 13. **Measurement result of output signal of PPG in Manchester code.**



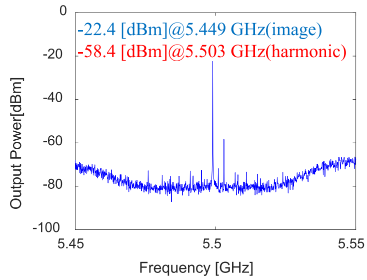
(a) Spectrum of input signal of RF tripler



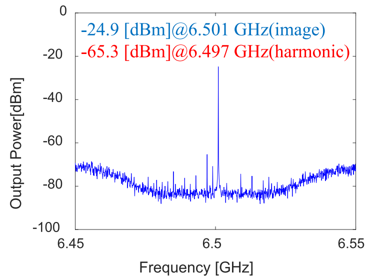
(b) Spectrum of output signal of RF tripler

FIGURE 14. **Measurement result of image enhancement technique using RF tripler in Manchester code condition for 1-bit BP-DS modulated signal.**

Manchester code eliminated by LPF are regenerated with a good noise shaping characteristics by the RF tripler. The output swing is 0.22 V_{pp}. To confirm the power of the harmonic and image component, the enlarged spectrums of regenerated image components at 5.5 GHz and 6.5 GHz are presented in 15(a), (b), respectively. From Fig. 15(a), (b), the output power of regenerated image components at 5.5 GHz and 6.5 GHz are −22.4 dBm and −24.9 dBm, respectively. The harmonic components can also be confirmed in 35 dB lower power



(a) Enlarged spectrum at 5.5 GHz



(b) Enlarged spectrum at 6.5 GHz

FIGURE 15. Enlarged spectrums of output signal of RF tripler in Manchester code condition in measurement.

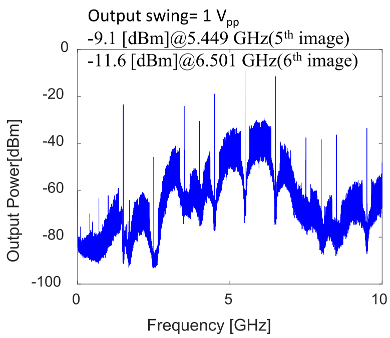


FIGURE 16. Spectrum with normalized peak-to-peak amplitude of output signal of RF tripler.

level than image components, which is same as the simulation result.

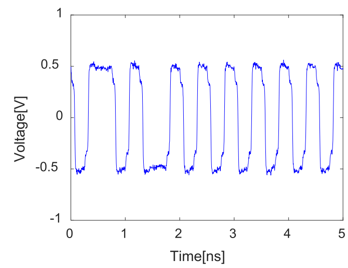
To compare with the simulation result more specifically, the peak-to-peak amplitude of output signal of RF tripler is normalized in MATLAB. Its spectrum with normalized peak-to-peak amplitude is shown in Fig. 16. With the normalized peak-to-peak amplitude, the output power of regenerated image components at 5.5 GHz and 6.5 GHz are −9.1 dBm and −11.6 dBm, respectively. The deviation between the result of simulation and measurement may be caused by the frequency characteristics of LPF and RF tripler, since both the LPF and RF tripler is ideal in the simulation.

C. MEASUREMENT RESULT IN QPSK CONDITION

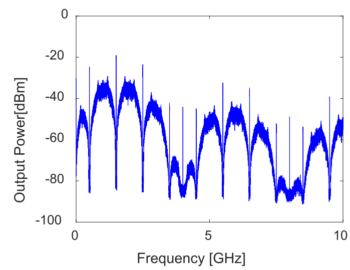
The 5Msps-QPSK (f_c=0.5 GHz) RF signal is also applied to the measurement. The measured waveform and spectrum of output signal of PPG is shown in Fig. 17(a), (b), respectively. The measured spectrum of input and output signal of RF tripler is shown in Fig. 18(a), (b) respectively. From the measurement result in QPSK condition, it is confirmed that the high order image components of 1-bit BP-DS modulated

TABLE 1. Comparison of simulation and measurement results of output power of regenerated high order image components with the normalized peak-to-peak amplitude.

Power [dBm]	ideal NRZ	ideal MAN	MAN+ tripler (sim.)	MAN+ tripler (meas.)
5^{th} image @5.5 GHz	-14.8 (CW)	-7.8 (CW)	-8.0(CW)	-9.1(CW) -11.9(QPSK)
6^{th} image @6.5 GHz	-16.3 (CW)	-9.3 (CW)	-10.7(CW)	-11.6(CW) -14.5(QPSK)

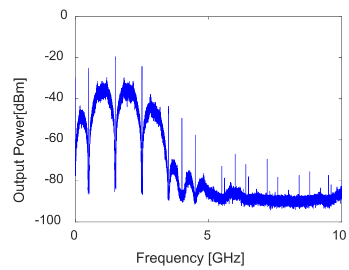


(a) Waveform

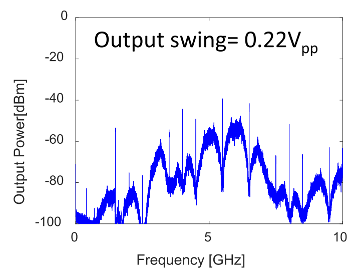


(b) Spectrum

FIGURE 17. Measurement result of output signal of PPG in Manchester code (QPSK condition).



(a) Spectrum of input signal of RF tripler

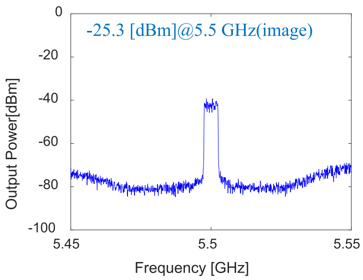


(b) Spectrum of output signal of RF tripler

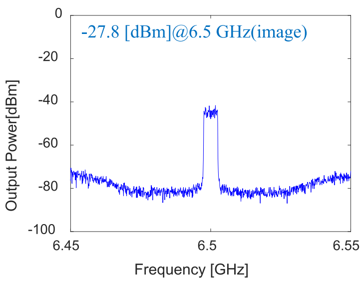
FIGURE 18. Measurement result of image enhancement technique using RF tripler in Manchester code condition for 1-bit BP-DS modulated signal (QPSK condition).

TABLE 2. Comparison with the previous works.

Reference	Nyquist zone	Datarate	RF frequency	Modulation	Code	Transmitter configuration	Power
[9]	Fundamental	3.5 Gbps	900 MHz	1.22M-QPSK	NRZ	DSP	N/A
[10]	Fundamental	3.2 Gbps	800 MHz	1.22M-QPSK	NRZ	DSP	N/A
[11]	Fundamental	3.9 Gbps	0.8/1.5 GHz	5M-QPSK	NRZ	DSP	-35.5/-37.7 dBm
[13]	1^{st} image	2.6 Gbps	1.95 GHz	5M-QPSK	NRZ	DSP	-15.8 dBm
[21]	Fundamental	13.5 Gbps	1 GHz	125M-16QAM	NRZ	DSP+Fiber	-21 dBm
[22]	Fundamental	10 Gbps	2.4 GHz	2.5M-16QAM	NRZ	DSP+Fiber	-8.5 dBm
[23]	Fundamental	10 Gbps	0.8 GHz	2.5M-16QAM	NRZ	DSP	-26 dBm
[24]	1^{st} image	25.78 Gbps	19.33 GHz	5M-QPSK	NRZ	DSP+Fiber	-28.6 dBm
[25]	1^{st} image	10 Gbps	7.5 GHz	5M-QPSK	NRZ	DSP+Fiber	-16 dBm
[27]	2^{nd} image	32 Gbps	40 GHz	20M-QPSK	NRZ	DSP	-30.6 dBm
[28]	6^{th} image	8 Gbps	26 GHz	5M-QPSK	Manchester	DSP+1-bit DAC	-31.9 dBm
This work	$5/6^{th}$ image	2 Gbps	5.5/6.5 GHz	CW	Manchester	DSP+tripler	-22.4/-24.9 dBm
This work	$5/6^{th}$ image	2 Gbps	5.5/6.5 GHz	5Msps-QPSK	Manchester	DSP+tripler	-25.3/-27.8 dBm



(a) Enlarged spectrum at 5.5 GHz



(b) Enlarged spectrum at 6.5 GHz

FIGURE 19. Enlarged spectrums of output signal of RF tripler in Manchester code condition in measurement (QPSK condition).

signal in Manchester code eliminated by LPF are regenerated with a good noise shaping characteristics by the RF tripler as well as in CW condition. The output swing is also 0.22 V_{pp}. The enlarged spectrums of regenerated image components at 5.5 GHz and 6.5 GHz are presented in 19(a), (b), respectively. From Fig. 19(a), (b), the output power of regenerated image components at 5.5 GHz and 6.5 GHz are −25.3 dBm and −27.8 dBm, respectively. In QPSK condition, the bandwidth of harmonic components whose center frequency is same as the image components, is three times wider than the image components which may degrade the ACLR of the regenerated image components. However, as shown in CW condition, since the power of harmonic components is 35 dB lower than that of image components, consequently, in QPSK condition, the regenerated image components have a good performance of ACLR as well.

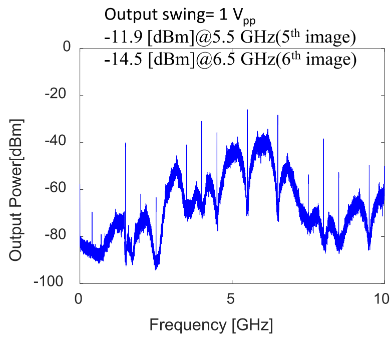


FIGURE 20. Spectrum with normalized peak-to-peak amplitude of output signal of RF tripler (QPSK condition).

The peak-to-peak amplitude of output signal of RF tripler in QPSK condition is also normalized in MATLAB. Its spectrum with normalized peak-to-peak amplitude is shown in Fig. 20. With the normalized peak-to-peak amplitude, the output power of regenerated image components at 5.5 GHz and 6.5 GHz are −11.9 dBm and −14.5 dBm, respectively.

The output power of regenerated image components in QPSK condition is 3 dB lower than that in CW condition. It is because in the consideration of the stability of DS modulation, as output of DSP whose amplitude 1 V_{pp}, the power of ideal 1-bit BP-DS modulated signal in QPSK condition is 3 dB lower than that in CW condition.

In Table 1, the output power of regenerated image components with normalized peak-to-peak amplitude is compared in the condition of the proposed image enhancement technique and ideal 1-bit BP-DS modulated signal in both NRZ and Manchester code. From the comparison, the measurement result is very close to the simulation.

As a conclusion of this section, first and foremost, in both CW and QPSK condition, it is confirmed in the measurement that the high order image components of 1-bit BP-DS modulated signal in Manchester code which are totally eliminated by LPF can also be regenerated with a good characteristics of noise shaping by RF tripler (odd-order RF multiplier) because of its nonlinearity, as the theoretical calculation and simulation presented in previous sections. The measured output power of the regenerated high order image components with normalized peak-to-peak amplitude in CW condition is very close to simulation result in condition of ideal 1-bit BP-DS modulated signal in Manchester code, which makes our assumption that the high order image components are part of the third order intermodulation of input signal more convincible. In QPSK condition, the regenerated image components also have a good performance of ACLR since the power of harmonic components is 35 dB lower than that of image components in CW condition. Since, in the consideration of the stability of DS modulation, the power of ideal 1-bit BP-DS modulated signal which is output of DSP in QPSK condition is 3 dB lower than that in CW condition, the output power of regenerated high order image components by proposed image enhancement technique in QPSK condition is 3 dB lower than that in CW condition.

Consequently, in this section, the proposed image enhancement technique using Manchester coding and RF tripler is proven to be effective by not only theoretical calculation and simulation but also measurement in both CW and QPSK condition.

V. CONCLUSION

In this paper, the image enhancement technique using Manchester coding and RF tripler is proposed. First and foremost, it is verified by theoretical calculation, simulation and measurement that the high order image components of 1-bit BP-DS modulated signal can be regenerated by RF tripler because of its nonlinearity and by using Manchester coding, the output power of regenerated image components can be enhanced further. In the previous works [21], [22], [23], [24], [25], [26], [27], even if the direct digital RF transmitter using image components can realize the miniaturization by removing mixer and LO, only low order (1^{st} or 2^{nd}) image components can be used because of the transmission loss. However, the proposed image enhancement technique using Manchester coding and RF tripler can regenerate the high order (5^{th} or 6^{th}) image components of 1-bit BP-DS modulated signal which are totally eliminated because of the transmission loss. Moreover, after the peak-to-peak amplitude of measured signal is normalized in MATLAB, the output power of regenerated high order image components is very close to ideal 1-bit data in Manchester code generated by an ideal 1-bit DAC based on inverter which is very difficult to implement in practical. It makes a contribution to the direct digital RF transmitter operating in higher frequency band with lower datarate compared with the previous works.

The Manchester coding can be easily realized by XOR gate without any other components in DSP so that there will not be much more burden on DSP, such as complexity, power consumption and so on. Moreover, it is obvious that RF tripler is much simpler than up-converter consisted of LO and mixer. Consequently, compared with the conventional transmitter using LO and mixer as an up-converter, the proposed image enhancement technique using Manchester coding and RF tripler is simpler and easier to implement in practical so that the miniaturization of transmitter can be achieved as well even in direct digital RF transmitter using the high order (5^{th} or 6^{th}) image components of 1-bit BP-DS modulated signal. Although there is an underlying computational cost of additional XOR gate in DSP, the proposed image enhancement technique is still very attractive because of its performance shown in this paper.

To verify the proposal, the theoretical calculation, simulation and measurement are conducted in Sect.II, III, IV, respectively. Since only two-tone CW signal is considered in the theoretical calculation, without the consideration of fundamental and noise components, there is deviation between the result of calculation and simulation. However, it still can be confirmed that, because of the nonlinearity of RF tripler, the high order image components of 1-bit BP-DS modulated signal in Manchester code can be regenerated with a good characteristics of noise shaping. In CW condition, the measured output power of regenerated high order image components at 6^{th} (5.5 GHz) and 7^{th} (6.5 GHz) Nyquist zone are −22.4 dBm and −24.9dBm, respectively. After the peak-to-peak amplitude of measured signal is normalized in MATLAB, the output power of regenerated high order image components are −8 dBm and −10.8 dBm, respectively, which is very close to ideal 1-bit data in Manchester code. In the QPSK condition, the measured output power of regenerated high order image components at 6^{th} (5.5 GHz) and 7^{th} (6.5 GHz) Nyquist zone are −25.3 dBm and −27.8 dBm, respectively. After the peak-to-peak amplitude of measured signal is normalized in MATLAB, the output power of regenerated high order image components are −11.9 dBm and −14.5 dBm, respectively. Since, in the consideration of the stability of DS modulation, the power of ideal 1-bit BP-DS modulated signal which is output of DSP in QPSK condition is 3 dB lower than that in CW condition, the output power of regenerated high order image components by proposed image enhancement technique in QPSK condition is 3 dB lower than that in CW condition.

At last, comparison with similar references which use the 1-bit delta-sigma modulator and consider transmission loss is shown in Table 2. From the comparison, because of the transmission loss, only the fundamental and low order image components of 1-bit BP-DS modulated signal are utilized in reference. However, in this paper, the high order image components at 6^{th} (5.5 GHz) and 7^{th} (6.5 GHz) Nyquist zone can be regenerated even if severe transmission loss is considered. Since the frequency is normalized in the theoretical calculation, the effectiveness of proposed image enhancement technique using Manchester coding and RF tripler is irrelevant to frequency, which means it should be effective in any frequency band as well.

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